SIMULATING WATER USAGE DURING UNCERTAIN TIMES IN THE SOUTHWESTERN UNITED STATES: AN ABM OF STRATEGIES AND POPULATION LEVEL ACTIONS

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ABSTRACT

Many of the nation's, and indeed the world's, most rapidly growing urban areas are in arid environments and face a future of greater water uncertainty. Arid cities therefore will benefit from a clearer articulation of the effects of climate change on urban water demand and supply and on community response to growing uncertainty. The Decision Center for a Desert City at Arizona State University is one of several new centers funded by the National Science Foundation to investigate human decision-making under climatic uncertainty. To address the uncertainty faced by water consumers, policy makers, and scientists, we are developing an agent-based model of water use (DesertWater) that integrates census data with municipality-supplied data on water use and implements plausible agent decision rules about water consumption, conservation, and media influence. We present our current version of the model and discuss our rational for the embedded decision rules.

Keywords: Water, ABM, agent-based model, uncertainty, policy, modeling

INTRODUCTION

Like an oasis, the Phoenix area — a complex of metropolitan cities — has emerged out of a desolate desert to become the fifth largest urban area in the United States. Having grown from a modest 300,000 in 1950 to 3.2 million in 2005, the population is expected to exceed 6 million by 2025 (Jacobs and Holway 2004). Not surprisingly, this influx of people is a continuing catalyst for new construction; residential areas, educational facilities, hospitals, retail centers, and other businesses are being developed to satisfy the evolving needs of the population. While Arizona's economy reaps the benefit of this expansion, it is questionable whether Arizona's ecology can sustain this rapid development.

The Phoenix transformation from saguaros and sand to concrete and cars is deceiving. Although metropolitan in appearance, Phoenix *is* a desert: it receives only 180 mm of annual precipitation and has typical summer temperatures of 115°F (Baker et al. 2004). As a result, the threat of a water shortage is omnipresent among today's residents of Phoenix, as it was with the earliest Sonoran dwellers — from the prehistoric Hohokam, who constructed 1,000 miles of irrigation canals, to the Euro-American farmers, who converted the dryland river valley into an agricultural paradise at the end of the nineteenth century (Gober 2005).

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Since its inception as a city, Phoenix, like most urban areas, has explored various options for water acquisition and management. These options collapse into three basic strategies: (1) seek more water, (2) conserve the available supply, or (3) implement some policy that involves strategies 1 and 2. Pros and cons exist for each strategy. Increasing supply is costly but will ensure a reservoir in drought conditions. Conservation works in theory, but the necessary amounts and strategies for implementation are not known. And an appropriate ratio of the two strategies may exist, but the proposed cost-benefit returns are purely suggestive and hypothetical. Given the lack of empirical data on all three strategies, debating the optimal strategy remains a scientific, policy, and political sport. There is simply not enough information about current social behavior, future climatic and hydrological change, or population growth and shifts to inform researchers about the best method to ensure the future water supply at a reasonable price.

Increasingly, it is recognized that even the best science will not significantly reduce uncertainty about global climate warming and the climate cycles that cause droughts, floods, hurricanes, and tornados. Society must learn to make better decisions in the face of uncertainty. The Decision Center for a Desert City (DCDC) at Arizona State University is one of several new centers funded by the National Science Foundation (NSF) to investigate human decision-making under climatic uncertainty. In 2004, the DCDC was founded to focus on water management decisions in the urbanizing desert of central Arizona. Under the charge of an NSF grant, the DCDC coordinates a program of interdisciplinary research and community outreach to improve water-management decisions in central Arizona. To that end, the DCDC studies the behavioral processes of individuals, examines how water managers make decisions, and then applies sophisticated models of decision science to water-allocation problems.

Decision-making, Incomplete Information, and Agent-based Modeling

The DCDC's central mission is to enhance and improve water management decision-making. Agent-based modeling is at the core of the decision-making tools being used at the center. In fact, a water-use agent-based model (ABM), named DesertWater, was immediately developed within this large multidisciplinary center. Why? Because an ABM can simulate processes in which decisions are decentralized and made by individuals and groups with different perceptions of uncertainty and attitudes toward risk. Our models quantify behavioral processes and then examine the reciprocal relationship between individual micro-social processes generated by explicit decision rules and group ontologies (Griffin 2003; Griffin et al. 2004; Schmidt et al. 2005). Groups, acting on the aggregate effect of individual rules, emerge as discrete entities that influence resource use and policy implementation and that, most noteworthy, by their actions, iteratively modify subsequent agent-level decisions. This reciprocal relationship between agent-level decisions and collective use of resources has been successfully modeled for other commodities. For example, North and colleagues (North 2001; Macal and North 2002) have examined the dynamics of electricity and natural gas consumption in competitive resource markets.

Modeling Water-use Decisions in the Southwest

Herein we present an overview of the rationale and algorithmic structure of the new, Repast-based, water-use ABM being developed at the DCDC. In its current form, aside from it having the more traditional aspects of any good ABM (e.g., a landscape populated with families composed of individuals [agents], with each agent having separate water-use preferences), we have developed several unique features within each agent of DesertWater that we hope provide a realistic representation and simulation of intra- and inter-familial water use.

Unique Model Features

First, aside from empirically based sociodemographic attributes (e.g., race, age, sex, income, and education obtained from Census data), agents are assigned values representing three relevant decision-making characteristics: (1) receptivity, (2) sensitivity, and (3) hierarchy. *Receptivity* refers to the ability to acquire or perceive information about either the relevant characteristic in the current scenario (e.g., price of water, media information) or the amount of water use by others. *Sensitivity* refers to the amount of change in water use that occurs in response to information obtained from other agents (via receptivity). *Hierarchy* reflects the intra-family influence that an agent has on other familial agents. For example, parents tend to have a higher rank than adolescents within the family (but not always), and if a parent decides to reduce water use, this change in behavior modifies the behavior of other family members.

Second, each agent is assigned a vision (i.e., sphere of perception of others) that extends from near neighbors (about 80%) to other agents far beyond its immediate geospatial location. This ability to perceive and retrieve information about another agent's water use is one of the factors that determines if, and by how much, personal water use is modified.

Third, the choice of which agents get monitored by other agents is based on tag matching (i.e., degree of homophily). Tags represent sociodemographic information (e.g., education, sex) that agents use to determine whether or not to attend to, and receive information from, other agents (Holland 1995).

Current Implementation

At this initial stage of model development, we are cross-referencing sociodemographic data with municipality-supplied water-use data. The data range from single-family households to office buildings; we have between 300,000 and 400,000 monthly water-use records for each year from 1995 to 2003. At this juncture of development, we are focusing on single-family households because the available data (e.g., usage) on this group are the most detailed. This provides an empirical basis for rule construction and expected consumer variation in response to price changes and media campaigns. Our objective is to construct agent interaction and information exchange rules that modify water use as a function of (1) water price fluctuations, (2) media information, and (3) perceptions of water shortage. Agents receive information about water through contacts with other agents, general perturbations (e.g., changes in water costs as indicated on water bills), or simulated media campaigns that encourage water conservation.

Consumer Information, Media Campaigns, and Population Penetration

Numerous U.S. states and several nations have instigated water conservation methods (e.g., see www.saws.org/conservation/, www.ec.gc.ca/water/, www.watercare.net/). Strategies to institute these measures generally fall into two categories: (1) the rough-and-ready Draconian (e.g., turn your water off or else) or (2) the Platonic, which emphasizes the cooperative tendencies of an informed public when adequate and truthful information is provided (Gilg and Barr 2005). Our water-use model is built on the latter style, along with the assumption that an informed public, when given a rationale with justification, will reduce consumption if members perceive that the problem is severe and observe that other people are also conserving water use. In effect, our model is built on this two-tier system: (1) media exposure and (2) near neighbor (agent) behavior. In its current form, the model integrates these two by using a differential media campaign (e.g., those least responsive are targeted more [e.g., Gilg and Barr 2005]), and each agent observes and responds inversely to the adjacency of other agents. The specific aggregate (i.e., population-level) response behavior is determined by one of two distributions: diminishing returns (i.e., each subsequent exposure unit of media has proportionally less impact) or a sigmoidal distribution with thick tails. The latter curve is based on the notion that consumer response will follow a contagion model; specifically, that some people are and will remain immune, and that among the susceptible others, the rates at which the new conservation behaviors move through the population will follow well-established epidemic trajectories (i.e., initially slow entry, then rapid explosion until the individuals that will eventually modify their behavior actually do).

Model Components and Overview

Census data are used to populate the households. Age determines initial water use for each family member and is calculated as a percentage of the initial water use seed. The first member of the family is an adult, and all tag characteristics (sex, race, education, and income) are derived from estimates of the likelihood as generated from the census data. Member *receptivity* (normal [truncated] distribution with a mean of 0.5, range of 1.0, standard deviation of 0.3) and *sensitivity* (normal [truncated] distribution with a mean of 2, range of 4, standard deviation of 2) are assigned randomly to each household member. The distribution (i.e., likelihood of being present) of tag characteristics for family members is also derived from census data. When the number of persons in the family is greater than three, there is a 15% chance that a grandparent is present. After populating the landscape and generating initial water-use data, the model generates weekly consumption estimates based on the assumed influence of the media and price. The process of generating these estimates is described next.

Observation and Adjustment by Comparison

Each week, 10% of the agents are randomly selected. These individuals then compare their water use to that of a pool of other similar agents, and from this comparison, they either reduce or increase their own water use accordingly. More specifically, after randomly selecting a household member (of the 10%), 200 random individuals who match on at least two tags with the selected individual are pooled such that 80% of them are within the same census tract, and an additional 15% are drawn from another, noncontiguous, tract. The final 5% are randomly selected from the remaining population. From this pool of similar individuals, 8–13% are selected, and their collective water use is averaged. From this value, an *influence score* is generated as the product of the percentage difference between the individual's water use and the pool's average water use and the *receptivity* of the individual (i.e., influence score = percentage difference × receptivity of the member). This influence score is then multiplied by the individual's *sensitivity* score to produce a new water use value. If the member who adjusts is either an adolescent or an adult, a percentage (30–75%) of this modification is distributed to all members of the family. A higher percentage is applied if the adult being modified is the head of the household.

Media — An Example

Although the emphasis has traditionally been on price manipulation to modify water consumption, it is probably more economically prudent to instill long-term behavior changes by using education. Within this perspective, we think of education as being two pronged. First, there is the formalized method of teaching conservation methods to young children. Second, there is the advocacy of reducing water use across the age range via satiation. We focus on this latter aspect of education. As currently implemented, we can inundate a selected population (i.e., chosen by receptivity) by using a myriad of media outlets, including television, radio, billboards, print, and mail. All outlets have equal weighting (i.e., influence) in the current model; the affect parameter of each outlet can be easily modified. We expect to implement a differential weighting scheme as we acquire either a theoretical rationale or empirical evidence.

OUTPUT

For data analyses and transfer, the output is in a comma-delimited file containing tick count (i.e., week), STFID (state federal ID [plot location]), (x, y) coordinates of the agent location, present water use of the agent, and present price of water for each agent every 52 ticks. In addition, we have graphic output of the (1) agents displayed in the (x, y) coordinate system, with color coding according to household water use (clicking on the agent provides household composition information including the current states of the individuals); (2) total water use of the whole population at any given point in time; (3) average water use according to age (Figure 1), and usage histogram (Figure 2); and (4) average water use according to water provider area (Figure 3). Figures 1, 2, and 3 provide visual feedback to the user at each iteration, and in response to any manipulation (i.e., change in media exposure) during a run.

FUTURE DIRECTIONS

In its current form, DesertWater provides some plausible scenarios for modifying Phoenix water use via a media conservation campaign. There are, however, several components that will need to be considered in future evolutions of the model. To remain consistent with the three arenas (i.e., science, policy, and politics) involved in determining the best strategy for water management, we approach our concerns and future intentions as specific to each.

Science

From a scientific perspective, the immediate concerns for improving the model focus on incorporating factors that will improve the ecological validity of DesertWater. For example, Phoenix is a major producer of citrus. Acres of orange groves and grapefruit trees are housed within the metropolitan and surrounding area. As a result, approximately 58% of all water use in

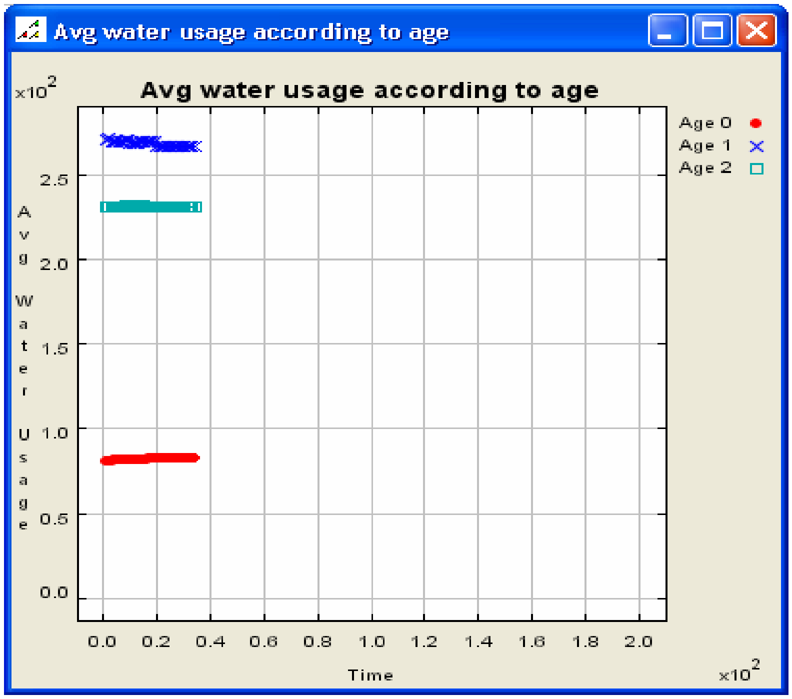

FIGURE 1 Water usage by age

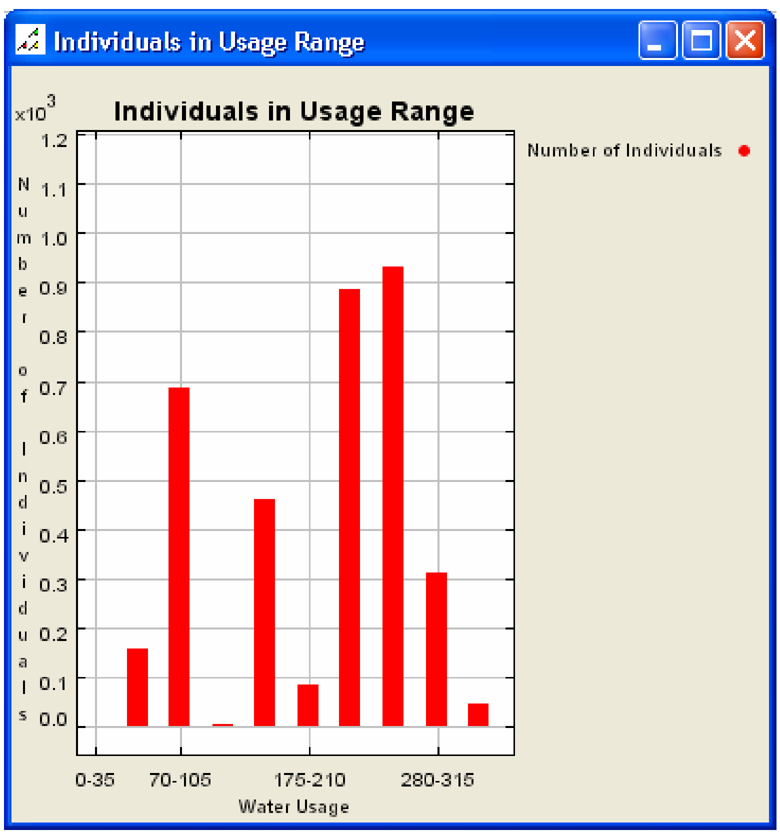

FIGURE 2 Usage histogram

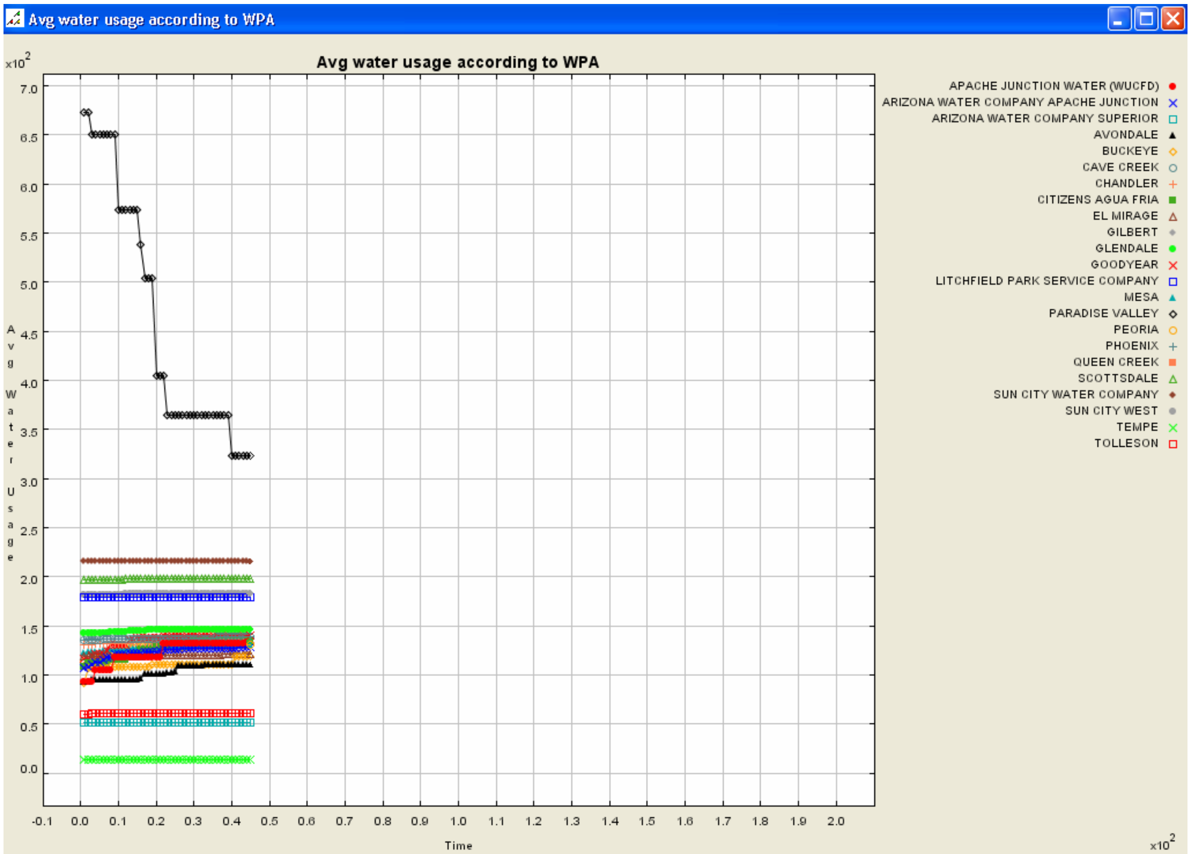

FIGURE 3 Water usage by provider

the valley can be ascribed to agricultural draws (ADWR 1999). Clearly, this is an aspect that needs to be included in the model.

Of the remaining 42%, industrial and commercial businesses account for a small proportion of water consumption, leaving a residential majority. While the current model already incorporates single-family households, it is limited in its application of family households for two reasons. (1) A large proportion of seasonal residents, college students, and low-income families live in multi-unit complexes (e.g., apartments, condominiums, and dormitories). (2) Baker and colleagues (2004) estimate that more than 70% of all residential water consumption is allocated for outdoor use (e.g., swimming pools, plants, and lawn care). Each of these factors has important implications with regard to capturing the true dynamics of the population and water-use landscape. Again, the incorporation of these two factors will be crucial for improving the validity of the model.

A final aspect is the trajectory of urban growth for the Phoenix metropolitan area. For the majority of U.S. metropolitan areas, geographic barriers limit spatial development. As a result, new construction typically requires the reallocation of land use. The Phoenix valley, however, is an exception to this constraint. Because Phoenix is housed within the desert and thus surrounded by vast open areas of desert, spatial growth is far from bounded. While the majority of new construction sites are converting agricultural lands to residential use, new areas of the desert are being transformed into housing developments in an outward direction, estimated at almost one-half mile per year (Gober and Burns 2002). This expansion has resulted in making the Phoenix region the largest contiguous metropolitan area in the United States (Melnick 1995).

One by-product of this increased construction is the nighttime attenuation of cooling by the re-radiating structures (Baker et al. 2002). This phenomenon, also known as the “urban heat island effect” has resulted in an increase of 0.1°C per year in Phoenix’s average minimum temperature over the past 50 years. In addition, Baker and colleagues also note that the number of “misery hours per day” (hours in which the temperature is above 38°C) in the valley has doubled since 1948. Not surprisingly, higher temperatures increase the need for cooling and irrigation — variables that are directly related to increased water demands (Larson et al. 2005). Given the climatic and ecological impact of urban sprawl in the Phoenix valley and the accompanying modification of water consumption, future iterations of the model will include scenarios describing how continued growth may modify water use.

Policy

Media

With respect to policy implementation, DesertWater currently maps the fluctuation of household water use as modified by exposure to water conservation media. The use of such a campaign is not novel; most local, national, and international campaigns typically include media messages that encourage residents to use water wisely. However, very few of these campaigns consider the varying likelihood of infiltration and response to those messages. By assigning our agents with sensitivity and receptivity thresholds, we have taken the first step toward modeling the complexity involved in the effectiveness of standard conservation campaigns.

Currently, the implementation of a differential response to media occurs randomly across the population of DesertWater. Yet, existing literature suggests that a conservation response is not random, but rather that there are four distinct patterns of response to media-driven conservation attempts: (1) consistent and high-frequency conservationists, (2) consistent and low-frequency conservationists, (3) individuals who practice conservation only if little or no personal sacrifice is required, and (4) individuals who engage in no conservation practices (Gilg and Barr 2005). In addition, this literature suggests that females, home owners, the well-educated, and the politically liberal are most likely to fall into groups 1 and 2, and that their male, renter, minimally educated, and politically conservative counterparts fall into group 4. Finally, Gilg and Barr note that high-income individuals are the most likely to cluster into group 3. For this particular study, older individuals were also more likely to cluster into groups 1 and 2, but this finding has not been replicated elsewhere; in fact, the opposite is typically found (Schultz et al. 1994).

With the exception of the uncertainty about age, there appear to be consistent patterns related to the demographic characteristics of individuals who engage in conservation behaviors. Given these findings, it appears that water conservation attempts by the media need to target individuals accordingly. In standard media campaigns, those in groups 1 and 2 may attend to messages to conserve water, but given the likelihood that they have already minimized use, it is not likely that the messages will result in further decreases for these individuals but rather will give them a psychological affirmation that they are doing their part. To get an added increase in conservation behavior from these individuals, it may be more efficient to use "reinforcement media." This type of media would focus on acknowledging how helpful these individuals have been, then subsequently encourage them to do just a little more. Reinforcement has been shown to be effective in perpetuating and increasing various behaviors at the individual and population level (e.g., Franzini et al. 1991), and it is likely a better method for appealing to individuals already engaged in the desired behavior.

Because individuals clustering into group 3 tend to have high incomes, it is hard to ascertain if their unwillingness to sacrifice comfort for water conservation is a result of the hurried lifestyle often seen in high-income families (e.g., working 10+ hours per day), the fact that they can afford higher water bills, or some combination of both. Clearly, standard water campaigns will not appeal to these individuals if they believe that they are entitled to use more water for either of the reasons stated above. Instead, messages targeting these families might be more effective if they recognized and empathized with their busy schedules, hard work, and stress *before* asking them to sacrifice the comfort of taking a longer shower or the convenience of running a half-empty dishwasher.

Unlike the individuals in group 3, conservation for the individuals in group 4 is not related to sacrifice. It is related to trust. These individuals consistently report disbelief in the media's call for action on conservation issues (Gilg and Barr 2005), citing exaggeration of the event (e.g., drought) or government attempts to deceive the population as the primary reason for their skepticism. Like those targeted to the other three groups, it is unlikely that standard media campaigns will affect the behavior of these individuals. To increase the likelihood of conservation actions by this group will first require addressing their bias toward media disbelief *before* asking them to join in the effort — the assumption being that very few people will act on something they think is false, especially when the action requires energy.

Given that four cluster patterns have been identified in the literature and that the demographic characteristics of each cluster are known, selecting distributions of agents that are skewed toward each of these media types will be the next likely step toward improving the model. In fact, by building scenarios that iterate the competing methods of standard media campaigns and differential media campaigns, we can tract the modification of water use in each method. Doing so should help us provide a case for the utility of our model in informing future policy decisions related to water conservation attempts via the media.

Education

While the media may constitute one way to encourage conservation, an additional, and perhaps superseding method, is the education of children. Intuitively, changing an already-existing behavior is much harder than shaping a new behavior. If young children receive the consistent message that using water wisely is the expected norm, they will be more likely to adopt water conservation behaviors and continue using them throughout adulthood. This effect has been used in other campaigns, ranging from encouraging seat-belt use to discouraging tobacco use, and it has been relatively effective (Roberts and Fanurik 1986; Jason and Pokorny 2002).

In addition to shaping children's water use behavior, educational methods may also vicariously modify adult behavior. Instead of relying on individual volition to comply in media campaigns, a family contagion effect may be created via education: children will bring the information home and act as the "policers" of household water use. Parents will, no doubt, vary in their degree of willingness to comply with the rule-oriented requests and reminders of their children. However, a child's personal request is harder to ignore than a billboard or television commercial and, as such, is a more probable means of effectively altering existing behavior.

As a result, we ultimately intend to build scenarios into DesertWater that include a distribution of agents receiving "education." Once implemented, we will be able to track the ability of these agents to modify water use in the short-term and long-term scenarios of the model. On an immediate basis, we hope to show the possibly of a contagion effect modifying overall household water use. Again, developing scenarios of competing methods — including education versus no education — will help establish the utility of our model for policy decision-making.

Politics

Policy and politics typically go hand-in-hand; ideally, the relationship is reciprocal, with each arena informing and influencing the other. With water, however, and specifically water in Arizona, this becomes a difficult task. While the policy makers desire to implement Platonic methods of "encouragement without enforcement," the politicians at the state level have serious doubts whether these methods can actually work or work in time (Arizona's Colorado River supply may soon be decreased by as much as 30%; see Larsen et al. working paper for details). As a result, the duel between Arizona water policy and politics has become a joust between nice and necessity. With the possibility of drought conditions and a decrease in an already limited supply, the politicians' concerns are legitimate. In order to ensure federal government assistance in the event of a water emergency, Arizona must show that it is trying to take the necessary measures to ensure that there is a long-term water supply for the Phoenix metropolitan area.

Water use behavior in the valley clearly needs to change, yet existing Platonic methods have not produced the desired result, and few politicians want to experience citizen backlash by imposing more Draconian methods of enforcement. Ultimately, water bans and the prevention of "water-unfriendly" landscaping may have to be imposed. In the interim, however, politicians continue to search for a less aversive yet equally effective strategy of decreasing water use in the Phoenix valley. Moreover, Arizona's water is regulated by individual water providers instead of the government, thereby complicating the policy and pricing structure of this commodity. These water providers designate the amount of available supply and price of water distributed in their area. Collectively, delegates from each area work together to set the ceiling price for water in Arizona. On one hand, the business approach to water management is beneficial to the residents, because it keeps the monthly water bill at a reasonable rate. On the other hand, it limits the ability of politicians to step in to offer either price incentives or disincentives in an attempt to modify water use.

Although the current state of water pricing is not a malleable topic, we have already incorporated this feature into the model. The basis for our decision was simple: people less responsive to other means of conservation attempts may be more or exclusively responsive to financial reinforcement or constraints. While we will primarily continue to focus on the things that do have the ability to be altered (i.e., media, education), we think it would be remiss on our part to not consider the possibility that altering the price may provide the "tipping point" needed to obtain a large-scale change in water-use behavior. We think that this scenario will be important if other methods fail, and the government is faced with making decisions about regulating the water business in Arizona.

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